Possible Effects of a Hidden Valley on Supersymmetric Phenomenology

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A hidden valley sector may have a profound impact on the classic phenomenology of supersymmetry. This occurs if the LSP lies in the valley sector. In addition to reducing the standard missing energy signals and possibly providing displaced vertices (phenomena familiar from gauge-mediated and R-parity-violating models) it may lead to a variable multiplicity of new neutral particles, whose decays produce soft jets and/or leptons, and perhaps additional displaced vertices. Combined, these issues might obscure supersymmetric particle production from search strategies used on current Tevatron data and planned for the LHC. The same concerns arise more generally for any model that has a symmetry (such as T-parity or KK-parity) realized nontrivially in both the standard-model and the hidden-valley sectors. Possible strategies for experimental detection are discussed, and the potential importance of the LHCb detector is noted.

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As analysis of Tevatron data proceeds and preparations for the Large Hadron Collider (LHC) continue, it is important to explore the phenomenology of experimentally-challenging models, so as to assure no phenomena are overlooked. Recent work on late-decaying gluinos [1, 2], and on multi-bottom or multi-tau decays of a Higgs [3, 4, 5] are in this spirit. The present article is aimed at continuing this effort. A class of "hidden-valley" models, in which a wide variety of new neutral resonances may arise, was presented in [6]. It was also argued that looking for neutral long-lived particles should be a high priority in Higgs searches [7]. Here it is shown how the hidden valley models, which can be attached without much experimental constraint to models that solve the hierarchy problem, including supersymmetry, extra dimensions and the little Higgs, can drastically change the phenomenology usually associated with those solutions.

The standard search strategy for supersymmetry (SUSY) — if R-parity is conserved — involves its missing energy signal. This is associated with the presence, in each event, of two of the lightest supersymmetric particle (LSP), a stable neutral particle. However, even with conserved R-parity, this signal may be reduced below the expected level, if the lightest standard model (SM) superpartner, which we will call the "LSsP", is not in fact stable. In this case the decay of the two LSsP's generates a "tagging" signal in essentially every supersymmetric event. This occurs in several contexts. In low-scale gauge mediated SUSY-breaking (GMSB) models, the LSsP is heavier than the gravitino, which is actually the LSP. The LSsP has a lifetime that is (from the point of experimental detection) largely unconstrained; typical decays to the gravitino plus visible particles may occur promptly, anywhere within the volume of the detector, or outside the detector. Other examples of theories with similar phenomena include models with degenerate Wino or Higgsino LSPs [8], models with light hidden-sector singlets [9], and R-parity violating (RPV) models [10]. In the latter class of models, the MET signature may be completely absent. Phenomenological signals of interest include metastable neutralino LSsP's decaying to a photon, Z boson or higgs boson plus missing transverse energy (MET), [11, 12]; metastable tau sleptons producing a tau plus MET, possibly generating a track with a kink [13]; three-body selectron or smuon decays [14]; metastable gluinos producing a jet or jets plus MET, possibly with a track and possibly at a displaced vertex [1]; track stubs from degenerate gauginos [8]; or even a metastable top squark [15] discoverable as a charged track or neutral particle ending at a vertex with a jet and often a lepton. Many interesting search strategies have been proposed, studied, and in some cases carried out [2, 16, 17, 18, 19]. These include searches for non-pointing and/or late photons or Z's, large negative-impact-parameter jets, out-of-time decays, etc. Final states, compared to the minimal-supergravity scenario, involve a reduced missing energy signal plus two sets of LSsP decay products. In all of these contexts, the decays of the LSsP reduce the missing energy signal, provide a "tag" that in some cases can be used to identify the supersymmetric events, generate new and often diagnostically-useful kinematic distributions, and potentially produce late decays that in some cases are easily seen and in other cases make detection an experimental challenge.

Hidden valley models can very easily produce LSsP decays that share many features with those listed above — a reduced missing energy signal and two sets of LSsP decay products. This is a general possibility whenever the LSP lies in the valley sector. Any production of SM superpartners leads to a cascade down to two LSsPs. Then each LSsP will decay to the v-sector, and its decay will therefore participate in (and thus both reveal and be confused by) whatever dynamics occurs in that sector. For this reason, hidden valley models can show additional subtle and experimentally relevant differences from other SUSY models.

In a typical hidden-valley model, the valley sector ("v-sector") has its own matter — valley quarks, or "v-quarks", and their superpartners, v-squarks — and its own gauge group, with v-gluons and v-gluinos. In confining hidden valley models, these v-particles are confined and form v-hadrons. In [6], the possibility was considered that v-particles are produced via a Z' decay; some of the v-hadrons produced in v-hadronization can then decay back to standard model particles, via an intermediate state Z' or Higgs boson. This is illustrated schematically in Fig. 1. V-hadron production in Higgs boson decays was considered in [7]. Here, we will consider a different scenario, in which the v-hadrons are produced in LSsP decays. In particular, as illustrated schematically in Fig. 2, production of SM superpartners leads, through cascade decays, to the appearance in the final state of two LSsP's. If the LSvP is lighter than the LSsP, then the LSsP will typically decay to an LSvP plus one or more v-hadrons, some of which in turn decay visibly. For simplicity we assume in this paper both that R-parity is conserved and that the LSvP itself is stable; if either is violated, the phenomenology may be richer still.

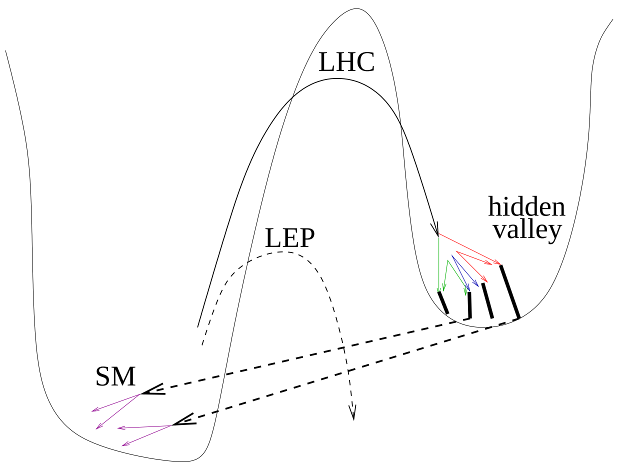

FIG. 1: Schematic view of production and decay of v-hadrons. While LEP was unable to penetrate the barrier separating the sectors, LHC may easily produce v-particles. These form v-hadrons, some of which decay to standard model particles.

Let us now consider how phenomenology of LSsP decays in hidden-valley models may differ in some ways from LSsP decays in other models. First, since the LSvP is a v-hadron, its decay to the LSvP may be accompanied by one or more long-lived R-parity-even v-hadrons, possibly with a substantial multiplicity. Some or all of these v-hadrons may in turn decay to visible (but often rather soft) particles. This decay pattern may make the decay products of the LSsP challenging to identify. An example of how this could occur in SM chargino-neutralino production is shown in Fig. 3. The two LSsP's (χ_1^0) decay to a v-quark Q and a v-squark $\tilde{Q}^*$; after hadronization, a number of R-parity-even v-hadrons and two R-parity-odd LSvP's ($\tilde{R}$) emerge. Some of the R-parity-even v-hadrons then decay to visible particles, leading to a busy and complex event. Second, many different v-hadronic final states may appear in LSsP decays, just as a large number of QCD hadronic states appear in τ and B decays. Acquisition of a large sample of events may therefore require a combination of search strategies. Finally, since the LSsP and/or some of the v-hadrons it produces may be long-lived and decay with highly displaced vertices, discovery and study of these events may require specialized, non-standard experimental techniques.

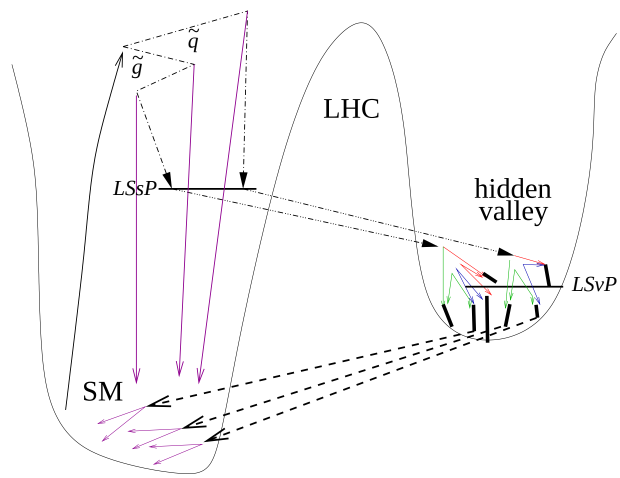

FIG. 2: Schematic view of production and decay of SM superpartners. Each superpartner decays to hard jets/leptons and an LSsP; the LSsP then decays to an LSvP plus other v-hadrons, some of which decay to softer jet/lepton pairs.

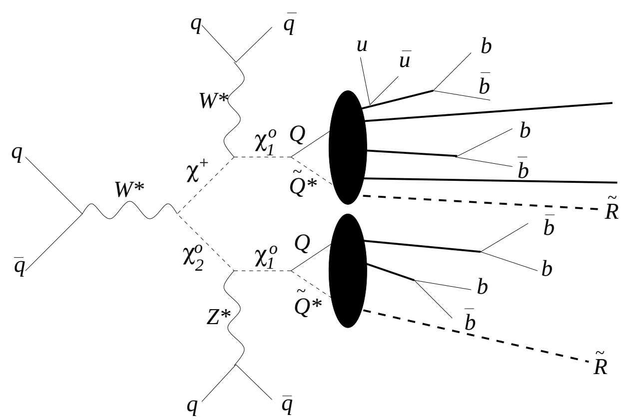

FIG. 3: The production and subsequent decay of a chargino and neutralino, showing the two LSsPs decaying to various v-hadrons, some of which decay visibly. Invisible R-parity-even (-odd) v-hadrons, are shown as solid (dashed) lines; in particular, an LSvP, labelled $\tilde{R}$, is produced in each of the LSsP decays.

The reverse situation — where the LSvP is heavier than the LSsP — is typically less dramatic, but still worthy of note. It leaves the bulk of SM SUSY signals unchanged, but can in some cases produce spectacular and challenging signals of its own. It will be discussed briefly below.

Meanwhile, analogous statements apply, with only a few adjustments, in other models with a conserved $\mathbf{Z}_2$

symmetry, such as extra-dimensional models (or their deconstructed cousins) with a spatial reflection symmetry in the internal dimensions (examples of which [20] inspired the work of [21].) The process in Fig. 3 requires only minor modification; for instance, the chargino and neutralinos might be replaced with parity-odd Kaluza-Klein excitations of the W and Z. Little-Higgs models with T-parity [22] are also potentially affected. Indeed, the essential point generalizes further, to include any conservation laws which are present and non-trivially realized in both sectors.

A. Hidden valley models

What is a hidden valley and why is it so-named? A hidden valley sector ("v-sector") has the following properties, illustrated in Fig. 1. First, like an ordinary hidden sector, it has its own gauge symmetries and matter particles, with the property that no particles (or at least no light particles) carry charges under both standard model gauge groups and under the v-sector gauge groups. Second, it has a mass gap, or at least a subsector with a mass gap, so that not all v-particles can decay down to extremely light invisible states which are stable or unobservably metastable. Third, an energetic barrier (a "mountain") limits cross-sector interactions between the SM sector and the v-sector; this barrier prevented v-particle production at LEP. Fourth, low points through the mountain (the elegant term "portals" was introduced recently in [23]) allow collisions of standard model particles at higher energy to produce v-sector particles. Fifth, massive long-lived v-sector particles can decay back to light standard model particles by tunnelling back through the mountains. These decays have strongly suppressed rates but are typically observable, sometimes with displaced vertices. And sixth — a fact we will exploit here — cross-sector interactions may also allow for the Higgs boson itself [7], and other neutral colorless SM particles such as the LSsP, to decay into the v-sector (Fig. 2.)

Since our main focus will be on models with an LSvP lighter than the LSsP, it is important to emphasize that such models are in no way unnatural. The mass spectrum of each sector depends both on dynamics within that sector and on the mechanism by which it learns about SUSY breaking. There simply is no reason for prejudice as to whether the two sectors have SUSY breaking at the same scale, or whether one has larger breaking than the other. For instance, suppose SUSY breaking is communicated strongly to one of the sectors but not the other. Since the interaction between the two sectors is suppressed, large SUSY breaking in one sector directly induces only moderate or small SUSY breaking in the other. Even if both sectors learn about SUSY breaking with comparable strength, it is a matter of detail whether the LSvP is heavier or lighter than the LSsP. Light v-gauginos are also easily obtained in many models (indeed it can be a model-building challenge to ensure they are not light) so this fact can easily lead to a light v-gluino.

As in [6], we will consider hidden valley models whose gauge groups are strongly-interacting and confining, with the mass gap generated by strong interactions or by a combination of strong interactions and the Higgs phenomenon. The strong interactions cause the v-sector particles to confine (at the scale Λ_v) and form v-hadrons. A number of long-lived resonances will result. The strong-interactions also cause v-parton showering, following which, when the energy scale of a process is large enough compared to Λ_v, large numbers of v-hadrons may be simultaneously produced.

A vast array of v-models are possible, with different details. For definiteness, let us take the minimal supersymmetric standard model (the MSSM) coupled via a Z' (of coupling $\alpha' \equiv g'^2/4\pi$ and mass $M' = 2g'\hat{v}$) to a v-sector of the form considered in [6], properly supersymmetrized. The v-sector will have v-quarks and v-gluons, and their superpartners, transforming under an $SU(n_v)$ gauge group, with coupling $\alpha_v \equiv g_v^2/4\pi$. The simplest models require two Higgs-like chiral multiplets ϕ_1, ϕ_2 in the v-sector, of opposite $U(1)$ charge under the Z', in order that anomalies cancel. As usual, $\hat{v} = \sqrt{2}\sqrt{\langle\phi_1\rangle^2 + \langle\phi_2\rangle^2}$, and $\tan\beta' = \langle\phi_2\rangle/\langle\phi_1\rangle$. Higgs mixing, along the lines of [24, 25], will lead to additional mixing between the two sectors [6, 7]. Unfortunately, the scenario suffers from strong irreducible model-dependence. First, there are a minimum of six Higgs-like electrically-neutral scalars (the usual three in the SM sector and three more in the v-sector, of which one in each sector is naturally CP-odd) and seven neutralinos (the usual four plus $\tilde{Z}', \tilde{\phi}_1, \tilde{\phi}_2$ in the v-sector.) Mixings among these particles can take many forms. Second, as in GMSB and RPV models, an unstable LSsP need not be neutral or colorless; thus there are many possibilities to consider. Finally, there are many choices for the properties of the Z'. A full study of parameter space is not feasible, and would not be particularly useful, given that this is just one of many models. Instead, an attempt will be made here to point out contexts where the phenomena are distinct from those in GMSB, RPV and other models with an unstable LSsP, and give signals that are interesting and often difficult (but probably not impossible) for the Tevatron and/or LHC experiments to detct.

B. Ordinary v-hadrons and their decays

Since every supersymmetric production event leads to production of v-hadrons, we start with a discussion of their spectrum, lifetimes and decay products. The spectrum of a v-sector consisting of a QCD-like theory with two v-quarks, one or both of which are light, was discussed in [6], and is reproduced in Fig. 4. If both v-quarks are light — the two-light-flavor (2LF) regime — compared to the confinement scale Λ_v, the spectrum is familiar from the real world, with all v-hadrons decaying quickly to a v-isospin triplet of light v-pions or to v-baryons. If one v-quark is light (the 1LF regime), the spectrum is not fully known; several v-hadrons with comparable masses but different spins and CP-quantum numbers are expected to be stable against decay to other v-hadrons. In both cases, the decay lifetimes [6] are such that displaced vertices are possible if the v-hadrons are light, and/or the Z' that couples the two sectors is heavy, and/or a flavor-changing neutral current is roughly of the right size.

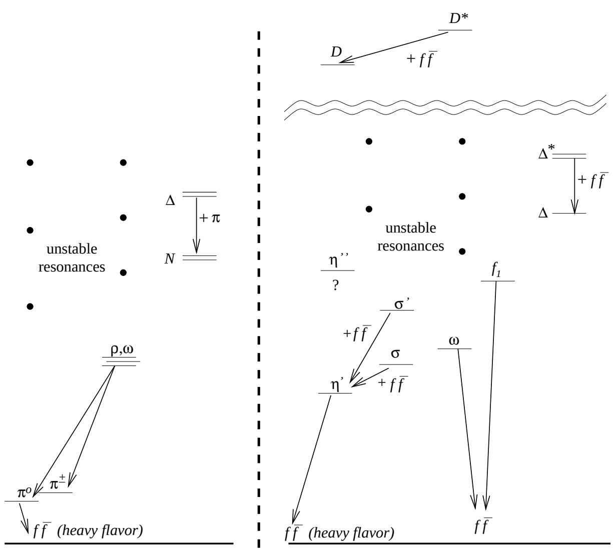

FIG. 4: Partial spectrum and decay modes in the two-light-flavor regime (left) and one-light-flavor regime (right); the latter is partly guesswork.

Some reanalysis of the results of [6] is necessary for the present context. In a model with sufficiently large Higgs mixing and, as is the case here, both CP-even and CP-odd Higgs scalars in both sectors, Higgs-mediated decays can compete with or exceed those mediated by the Z' discussed in [6]. Note also that it was assumed in [6] that the Z' is light enough to be produced at the LHC; here, v-hadron production proceeds via a different mechanism, so there is no such constraint. This widens the range of possible v-hadron lifetimes and increases the likelihood that the Higgs sector will dominate v-hadron decays. The discussion will be brief, since so many other models can be written in which similar or novel mechanisms for long-lived particles can be obtained. The important points to emphasize will be these: (1) the decays need not be unobservably slow; (2) the decays need not be prompt; (3) heavy flavor is likely to be common in the final state; (4) decays to $\tau^+\tau^-$ are expected, and branching fractions to $\mu^+\mu^-$ pairs may be measurable. To keep this already broad discussion under control, we will assume a relatively light mass spectrum, for which decays to $t\bar{t}$, WW and ZZ are unimportant or simply absent. If they are present, some additional experimental issues arise.

If we assume that mass splittings from SUSY breaking in the v-sector are large compared to Λ_v, then the lightest v-hadrons are the R-parity-even states shown in Fig. 1 of [6]. The decays of these v-hadrons to the SM-sector can occur through the v-Higgs sector (whose states we will simply refer to as ϕ) or via the Z'. Although the Higgs sector may have a light ϕ, the Z'-mediated decay can be stronger than the ϕ-mediated decay if $\hat{v}$ is not too large, and/or Higgs mixing is not too large, and/or the Higgs Yukawa coupling to the v-quark and v-squark is not large. For definiteness, let us consider a simple case. To see whether the Z'- or ϕ-mediated decay is most important, we estimate both processes neglecting the generally-subleading effect of interference. In the 2LF regime, the most interesting particle is the π_v^0. Its decay via a Z' to $b\bar{b}$ was computed in [6], where a substantial suppression for small π_v^0 masses, and a resonant enhancement for $m_{\pi_v^0} \sim m_Z$, was noted:

$$\Gamma_{\pi_v^0} = \frac{3}{32\pi}\frac{1}{\hat{v}^4}\frac{Q_H^2 f_{\pi_v}^2 m_{\pi_v}^5}{(m_{\pi_v}^2 - m_Z^2)^2} m_b^2 \ . \qquad (1)$$

For $4m_b^2 \ll m_{\pi_v}^2 \ll m_Z^2$,

$$\Gamma_{\pi_v^0} \sim 6\times 10^9 \ \mathrm{sec}^{-1} \frac{f_{\pi_v}^2 m_{\pi_v}^5}{(20 \ \mathrm{GeV})^7}\left(\frac{5 \ \mathrm{TeV}}{\hat{v}}\right)^4 \ . \qquad (2)$$

Here Q_H is the charge of H under the Z', taken to be 2/5 for the numerical estimate. In comparing to [6] we have used $m_Z' = 2g'\hat{v}$ in this model. For $m_{\pi_v} \ll m_Z$ and $\hat{v} \gtrsim 3$ TeV, this is macroscopic. Note $\hat{v}$ in [6] was taken of order 5–10 TeV to allow reasonable production rates of v-quarks at the LHC, but here $\hat{v}$ could be much larger, as large as 100 TeV or even more, without losing the v-hadron phenomenology.

An estimate of the π_v^0 decay via a CP-odd scalar of mass m_A can be obtained as follows. (A full calculation is straightforward but beyond our present needs.) If the lightest CP-odd scalar is much heavier than the π_v^0 and if its component in the SM-sector (v-sector) is $\cos\theta_-$ ($\sin\theta_-$), then, defining $\tan\beta \equiv v_u/v_d \equiv \langle H_u\rangle/\langle H_d\rangle$, we have

$$\Gamma_{\pi_v^0} = \frac{3}{8\pi}\frac{\theta_-^2}{\hat{v}^2 v^2}\frac{f_{\pi_v}^2 m_{\pi_v}^5}{(m_{\pi_v}^2 - m_A^2)^2} m_b^2 \ f(\beta') \ \tan^2\beta \qquad (3)$$

The function $f(\beta')$ could most naturally be either $\tan^2\beta'$ or $\cot^2\beta'$, depending on the coupling of A to the light v-quarks. In this expression θ_-, the mixing parameter between the CP-odd scalars in the two sectors, is assumed small. Its natural size (if it is induced by D-terms as in [24] — though this can be evaded in nonminimal models with F-terms, as was used in [7]) is of order $2Q_H v/\hat{v}$. Consequently both (1) and (3) naturally scale as $\hat{v}^4$. The two processes are parametrically of the same order; details of the spectrum and mixing angles determine which is larger. For any m_{π_v} (except very near the Z or A masses) there exist ranges of reasonable $\hat{v}$ for which the π_v^0 decay is respectively prompt, displaced, or external to the detector. The π_v^0 branching fractions are similar to those of a CP-odd Higgs boson of the same mass; in the decay via a Z', this is due to helicity suppression [6]. The $\pi_v^\pm$ may be stable, in which case it contributes only MET, but in some models the $\pi_v^\pm$ will decay through a flavor-changing coupling. In this case its lifetime is longer than that of the π_v^0, by an amount determined by the strength of this coupling.

In the 1LF regime, the η'_v decay is similar to that just described for the π_v^0. The ω_v decays predominantly via an off-shell Z' to $f\bar{f}$ (f any SM fermion) with branching fractions determined by the Z and Z' [6]. Its decay is much faster than that of the η'_v; roughly,

$$\Gamma_{\omega_v} \sim 10^{18}\ \mathrm{sec}^{-1} \left(\frac{m^5_{\omega_v}}{200\ \mathrm{GeV}}\right)^5 \left(\frac{5\ \mathrm{TeV}}{\hat{v}}\right)^4 . \tag{4}$$

The decay $\omega_v \to \eta'_v f\bar{f}$ is generally suppressed unless mass splittings permit an on-shell decay to $\eta' Z$ or $\eta' h$.

As for the lightest R-parity-odd v-hadron, it generally consists of a (typically heavy) v-squark or v-gluino bound to one or two v-quarks or v-gluons. Such a heavy-light system is well studied in the context of SM heavy-quark mesons. elsewhere.) The lightest R-parity-odd v-hadron "$\tilde{R}$", the LSvP, is stable against v-hadron decays, and may be truly stable if it is the LSP. Most other R-parity-odd v-hadrons have v-strong decays $\tilde{R}$ plus other v-hadrons. However, the spin splitting between the LSvP $\tilde{R}$ and its first excitation $\tilde{R}^*$, which decreases as $m_{\tilde{R}}/\Lambda_v$ increases, may be small enough to stabilize the latter against v-hadronic decays. The decay $\tilde{R}^* \to f\bar{f}\tilde{R}$, which may occur via an off-shell Higgs or Z' boson, may be experimentally interesting.

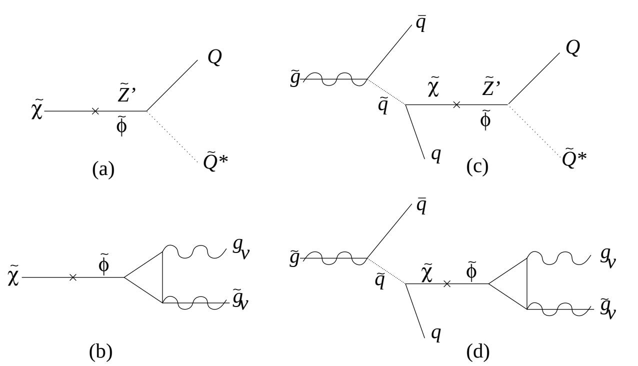

FIG. 5: Various possible decays of an LSsP to an LSvP. (a) At one extreme, prompt neutralino decays to a v-quark and v-squark via mixing of the neutralino with the $\tilde{Z}'$ or $\tilde{\phi}$. (b) Slow decay of a neutralino to a v-gluon and v-gluino via a v-quark/v-squark loop. (c) Slow decay of a gluino to $q\bar{q}$ plus a v-quark and v-squark. (d) Very slow decay of a gluino to a v-gluino.

C. LSsP decay rates

We now turn to the decay of the LSsP to the v-sector. A complete analysis of the possibilities is beyond the scope of this article. Here the aim is to consider generally the signals that might arise, in order to initiate discussions of the experimental implications and to motivate future studies.

Let us first see that the LSsP's decay may be prompt, unobservably long, or displaced. Initially we will focus on the scenario where M and m, the masses of the LSsP and LSvP, satisfy $M - m \gg \Lambda_v$; we will deal briefly with other cases later. The LSsP decay rate depends of course on the precise v-spectrum and the composition of the LSsP and LSvP, and relevant mixing angles can vary widely, so we content ourselves with rough estimates here. For obtaining figures of merit, we will take typical mixing angles between the SM-sector neutralinos and the v-sector neutralinos to be of order $\theta_v \sim v/\hat{v}$, which is typically ~ 0.05; this assumption will not be crucial to the conclusions.

If the LSsP is a neutralino, then as shown in Figs. 5a and 5b, its decay can occur either through a $\tilde{Z}'$ or $\tilde{\phi}$ coupling to v-quark and v-squark $Q\tilde{Q}^*$, or through a $\tilde{\phi}$ coupling to a v-gluon and v-gluino $g_v\tilde{g}_v$. If the $\tilde{Z}'$ dominates, then the decay rate is of order

$$\begin{aligned}\Gamma_{\tilde{\chi}} &\lesssim \alpha' m_{\tilde{\chi}} n_v \theta_v^2 \\ &\sim 2\times 10^{22}\ \mathrm{sec}^{-1} \left(\frac{\alpha'}{0.01}\right)\left(\frac{m_{\tilde{\chi}}}{200\ \mathrm{GeV}}\right) \\ &\quad \times \left(\frac{\theta_v}{v/\hat{v}}\right)^2 \left(\frac{5\ \mathrm{TeV}}{\hat{v}}\right)^2 .\end{aligned} \tag{5}$$

(In the last step we took n_v, the number of v-colors, to be 3.) This decay is prompt, even accounting for possible additional phase-space suppression. If instead an intermediate $\tilde{\phi}$ dominates through couplings to $Q\tilde{Q}^*$, the coupling α' in (5) should be replaced by a coupling $y_Q^2/4\pi$, where y_Q is the coupling of the relevant v-quark to the relevant v-Higgs, but the decay remains prompt. If there are no light v-squarks, a neutralino decay to a v-gluino can occur through a loop, as in Fig. 5b, and is of order

$$\begin{aligned}\Gamma_{\tilde{\chi}} &\lesssim \frac{n_v^2 - 1}{4\pi} m_{\tilde{\chi}} \theta_v^2 \left(\frac{\alpha_v n_v n_H m_{\tilde{\chi}}}{48\pi\hat{v}}\right)^2 \\ &\sim 2\times 10^{16}\ \mathrm{sec}^{-1} \left(\frac{m_{\tilde{\chi}}}{200\ \mathrm{GeV}}\right)^3 \\ &\quad \times \left(\frac{\theta_v}{v/\hat{v}}\right)^2 \left(\frac{5\ \mathrm{TeV}}{\hat{v}}\right)^4 .\end{aligned} \tag{6}$$

Here α_v and n_v are the coupling and number of colors of the v-confining gauge group, and n_H is the number of heavy v-quarks obtaining masses through ϕ; in the above estimate we took $n_v = 3$ and $\alpha_v n_v n_H \sim 1$. We have assumed v-squark masses are parametrically of order $\hat{v}$; if they are much larger they will further suppress the amplitude. In some regions of parameter space, this decay can occur with a displaced vertex, though it is often prompt.

Suppose instead the LSsP is a gluino. Then it may decay to a v-quark and a v-squark plus either a quark-antiquark pair (as shown in Figs. 5c) or a gluon (not shown, and typically with a smaller branching fraction).

The rate for the former, if dominated by gaugino exchange, is of order or smaller than

$$\Gamma_{\tilde{g}} \lesssim \frac{\alpha_s \alpha_2 \alpha' N_f n_v m_{\tilde{g}}^7}{m_{\tilde{q}}^4 m_{\tilde{\chi}}^2} \theta_v^2$$
$$\sim 6 \times 10^{15} \mathrm{sec}^{-1} \left(\frac{\alpha'}{0.01}\right) \left(\frac{m_{\tilde{g}}}{500 \text{ GeV}}\right)^7 \left(\frac{\theta_v}{v/\hat{v}}\right)^2$$
$$\times \left(\frac{1 \text{ TeV}}{m_{\tilde{q}}}\right)^4 \left(\frac{1 \text{ TeV}}{m_{\tilde{\chi}}}\right)^2 \left(\frac{5 \text{ TeV}}{\hat{v}}\right)^2 . \quad (7)$$

Here $\alpha_2 = g_2^2/4\pi$ is the coupling of the SM $SU(2)$ group factor, and N_f is the number of squarks of mass $m_{\tilde{q}}$; we took $N_f = 1$ and $n_v = 3$ for this estimate. This estimate is very rough and subject to large parameter dependence and phase space suppression. The direct coupling of the $\tilde{Z}'$ to the intermediate-state SM squark $\tilde{q}$ may well be more important; the rate is as above with the replacement $\alpha_2\theta_v^2/m_{\tilde{\chi}}^2$ with $Q_q^2/\hat{v}^2$, where Q_q is the charge of $\tilde{q}$ under the Z' [6]. A similar formula governs if higgsino-exchange is dominant, with a possible Yukawa-coupling (or v-coupling) suppression. This decay mode may be prompt or may produce a displaced vertex within the detector. Since the gluino is long-lived compared to the QCD scale, it will undergo hadronization, and its phenomenology is similar to that discussed in [1]. If no v-squarks are kinematically available, the gluino will decay to a v-gluino and a v-gluon, as shown in Fig. 5d. This is a very slow decay, and will generally occur outside the detector — or, if the hadron containing the gluino stops within the detector [1], it will have an out-of-time decay, such as searched for in [2]. The final state, containing v-hadrons as well as a quark and antiquark, differs somewhat from that considered in [1, 2], but is presumably still constrained.

Finally, decays of LSsP sleptons or squarks are intermediate between these possibilities. The decays are typically (but not always) prompt. A lepton or quark accompanies the v-hadrons in each LSsP decay. A variety of phenomena are possible; we will not give an exhaustive list here.

Let us summarize the phenomenological possibilities and reemphasize the main points. Neutralinos can directly link the two sectors and decay promptly. Charged matter (LSsP squarks, sleptons or charginos) must first emit neutralinos to cross the barrier between the sectors. Gluinos and v-gluinos must first couple to charged matter, which in turn couples to neutralinos, in order to communicate between the two sectors. The more steps required to cross from one sector to the other, the slower the LSsP decay rate. The multiple possible choices for LSsP and LSvP allow great variability in the LSsP lifetime. Also, as in GMSB models, a charged or colored LSsP must decay to a standard model particle in addition to v-hadrons, enriching the signals.

It is important to emphasize that in contrast to [6, 7], where it was vital that the scale $\hat{v}$ of the "portal" between the two sectors not be much above 10 TeV, in order that v-hadrons be produced with measurable rates, the present scenario has a much weaker requirement, especially in the 1LF regime. The above formulas for LSsP and v-hadron decay rates show that values of $\hat{v}$ in the 100 TeV range, or even higher, may still give detectable decays. If this turns out to be the case, LSsP decays will be the only source of v-hadron production, and the only clue to physics both in the v-sector and at the 100 TeV scale.

D. Final states of LSsP decays

The final state of the LSsP decay is affected by the v-strong interactions; it contains one $\tilde{R}$, plus other v-hadrons (including possibly an even number of additional R-parity-odd states.) In the 2LF regime of the theory studied in [6], the LSsP typically decays to one $\tilde{R}$ and n $\tilde{\pi}_v$, where n will fluctuate from event to event. (For instance, if $m_{\tilde{\chi}} \sim 200$ GeV, $m_{\tilde{R}} \sim 60$ GeV, $m_{\pi_v} \sim 20$ GeV, experience from SM τ decays would suggest $n \sim$ 0–4.) The π_v^0 will decay visibly; whether the $\pi_v^{\pm}$ decays visibly is model-dependent. The 1LF regime of the same theory probably will have smaller n for the same Λ_v, but has fewer invisible v-hadrons, and possibly a larger average number of visible jets and leptons per v-hadron [6]. The final state of each LSsP will consist of MET and up to $\sim 2n$ moderately soft and poorly isolated objects, with a preponderance of heavy-flavor quarks and τs. If all v-hadron decays are prompt, displaced vertices from the many b mesons may be notable, but the low momentum of the b quarks and their overlapping jets may make b-tagging less than maximally efficient. If some v-hadrons decay late, there may be as many as n highly displaced vertices for each LSsP.

In some kinematic regimes, the signals may be similar to those familiar from other models, such as those with GMSB. For instance, if $M - m \sim \Lambda_v$ (where M and m are the masses of the LSsP and LSvP,) the predominant decay of the neutralino LSsP may be $\tilde{\chi} \to \tilde{R}\pi_v^0$, that is, $n = 1$. If m_{π_v} or f_{π_v} are too large, the decays $\tilde{\chi} \to Z\tilde{R}$ or $\tilde{\chi} \to h\tilde{R}$ may be important, or, if even this is kinematically forbidden, then three-body decays such as $\tilde{\chi} \to f\bar{f}\tilde{R}$ may result. In such contexts the final state of each LSsP still has ample MET, along with a SM fermion pair that accompanies every (or almost every) LSsP decay. With luck, this may be a relatively hard $b\bar{b}$ or lepton pair. Then every supersymmetric event has four moderately hard fermions, and the MET signal is reduced by a relatively small factor, so standard SUSY searches with a demand for leptons or extra b-tags may be able to isolate a signal. But the larger is $M - m$ relative to Λ_v, the larger is n, giving an unfamiliar final state with reduced MET, many soft jets and/or leptons, and possibly many displaced vertices.

The degree to which the MET signal is reduced is model-dependent. A very crude estimate is simply as follows. If $m, \Lambda_v \ll M$, and k of the n v-hadrons are invisible, then on average the MET signal is reduced, relative to the same event with the LSsP escaping the detector, by a factor of order $(k+1)/(n+1)$. For $\Lambda_v \ll m \sim M$, the reduction factor approaches $m/M + [k/n](1-m/M)$. The largest reduction in MET thus occurs for $m \ll M$, n large (requiring $M - m \gg \Lambda_v$), and $k \ll n$ (requiring most v-hadrons decay visibly). For instance, the 1LF regime with $M \gg m \gg \Lambda$ would exhibit a very strong reduction of the MET signal, as would the 2LF regime if the $\pi^\pm$ decays visibly. Conversely, a substantial reduction can only be avoided if most v-hadrons decay invisibly or if $m \sim M$. Since SM backgrounds fall steeply with MET, any appreciable reduction in the MET signal greatly decreases the signal-to-background ratio throughout the MET distribution. Without the strong MET signal, and in the absence of easily identifiable "tagging" objects such as photons, novel search strategies may be needed to discover supersymmetric particle production.

E. Production and detection

At the Tevatron, the number of supersymmetric events in models not excluded by LEP could be as large as 100 to 1000 in current data. In the hidden-valley scenario, the detection of these events could be made much more subtle — though possibly easier, in the end — than expected. Consider again Fig. 3; would any analysis so far have detected such phenomena? On the one hand, it is not obvious that a hundred events with 4 to 8 soft b jets and relatively low MET, possibly with additional hard jets, possibly without, would yet have been noticed. The trigger efficiency on such events, assuming a trigger on muons, jets and/or MET, might well be of order 20-40 percent, so a substantial sample would have been recorded, but no typical search strategy might have isolated them as yet. On the other hand, since these events may have multiple highly displaced vertices, more searches for such vertices might expose these events directly.

At the LHC, the number of supersymmetric events produced may be enormous, perhaps 10^3–10^5 each year. The number of v-hadrons produced in each event may be of order 2–10. With 10^3–10^6 v-hadrons, branching fractions of a percent or less become experimentally interesting. Both triggering and event-selection may benefit from the many τ pairs and μ pairs (either produced directly or in b and τ decays) that will be present in these events. If a clean and sufficiently large sample of such events is obtained, perhaps through highly-displaced vertices from LSsP or v-hadron decays, it may even be possible to do some precision spectroscopy using lepton-pair invariant mass distributions, looking for resonances or kinematic endpoints that could arise from $\omega_v \to \mu^+\mu^-$, $\tilde{R}^* \to \mu^+\mu^-\tilde{R}$, etc. (Note there will be an irreducible combinatoric background from leptons arising in v-hadron decays to b's and τ, so high statistics and wise selection criteria will be important to find such kinematic features.) Conversely, in scenarios where the number of supersymmetric events is small, the highly-displaced vertices may be the key experimental signal by which supersymmetric particles (as well as, simultaneously, the v-sector) are first discovered, and clean samples are obtained.

Because both the LSsP and the v-hadrons in its decay can be long-lived, with various possible lifetimes, a wide variety of track patterns must be searched for. The LSsP decay may produce, for example, (i) a single vertex with a very large number of tracks, or (ii) a set of displaced vertices with multiple tracks that themselves all point back to a single displaced point with very few or no tracks, or (iii) a displaced vertex with many tracks, followed by other vertices with fewer tracks. Other possibilties abound. Many of these tracks or clusters of tracks may not point back, even approximately, toward the beampipe, making them hard to identify. It may be worth considering how best to design tracking algorithms to recognize candidates for such decays, so as to allow events to be flagged for further off-line analysis. The challenge may be significant, since many of these events may be very busy, with the various displaced vertices occuring within clusters of tracks emerging from overlapping soft jets.

Looking for highly displaced vertices (and/or for many slightly-displaced vertices) will be difficult and may be computationally expensive. It is therefore important to devise effective strategies for selecting events that are especially likely to contain them. It has been suggested that high-precision timing information may serve to identify events that contain highly-displaced vertices [17]; while this study focuses on late-arriving photons, it presumably also applies to hard electrons and to pi_0 decays to photons. Other approaches might include the following:

- A sample of events with moderate MET (with or without high-p_T jets) could be searched both for an unusual number of displaced vertices inside the beampipe, and for vertices outside the beampipe.
- Events that already have three or more displaced vertices detected within the beampipe would be good candidates for additional vertices outside the pipe.
- Events with multiple *and not necessarily isolated* muons would form a good sample in which to check for a μ pair emanating from a out-of-pipe vertex. The vertex might have several other tracks (expected in $b\bar{b}$) or be non-pointing (expected in $\tau^+\tau^-$) or, if there are no other tracks, have an invariant mass far from any known resonance. The scenarios covered would extend somewhat beyond those affected by the search carried out in [18], which focuses on cleaner signals with no background, and has lower than maximal acceptance.
- Another interesting sample would include events with two or more "trackless" jets — jets that lack

stiff tracks pointing near the jet axis. Within such jets, one could look for muon candidates registering in the muon chamber but which lack a corresponding track in the innermost detector elements. Such muon-candidates within trackless jets would suggest the presence of a displaced vertex outside the innermost tracker.

- Additional searches for displaced Z or h candidates, in channels other than $Z \to e^+e^-$ searched for in [19], would be welcome, perhaps using the negative-impact-parameter tracks method discussed in [12, 15].

If no readily-produced new particles decay with highly displaced vertices, additional techniques may need to be considered. Although many supersymmetric events with a decaying LSsP may have 4 or more b quarks and/or τs, the efficiency for tagging of b quark jets and τ identification in an environment such as that shown in Fig. 3 is surely unknown, and probably low. Also, jet reconstruction in such a busy event will be problematic. A program of studies, along the lines of [5], but more extensive and involving new Monte Carlo tools and full detector simulations, will be needed to clarify these issues and allow for effective event selection.

As an aside, let us note that, once a working strategy for event selection has been established, it may be possible to test an important prediction of this scenario, one which is also true of other scenarios with LSsP decays. Some fraction of events may produce two highly boosted LSsP's, which may in turn produce collimated and readily identifiable decay products. These products roughly indicate the momentum directions of the LSsP's. Since the missing transverse momentum in such events should come mainly from the LSvP's and other invisible v-hadrons from the LSsP decay, the direction of the missing momentum should lie between the two putative LSsP momentum directions. This prediction is a test of the two-stage process that forms the events: (1) cascade decays of a pair of SM supersymmetric particles lead to two boosted LSsP's, and then (2) the decay of the two LSsP's produces two collimated clusters of both visible and invisible particles.

F. A heavier LSvP

Let us briefly consider the situation when the LSvP is heavier than the LSsP. In this case, the vast majority of events in which SM superpartners are produced will not be affected by the v-sector. Only v-sector production, assuming it occurs at all, may be affected in interesting ways. In supersymmetric v-production, each event will have two LSvP's, each decaying to an LSsP, but the decay of the LSvP itself may not be striking. For instance, a v-squark LSvP may simply decay (promptly) as $\tilde{Q} \to Q\tilde{\chi}$, where $\tilde{\chi}$ is a neutralino LSsP. This decay occurs within a v-hadron $\tilde{R}$, so the final state will often contain one or more v-hadrons. But in this context, v-quark pair production and v-squark pair production may not differ greatly. In many scenarios, both classes of events will produce multiple visible and invisible v-hadrons; the v-squark events will have larger MET on average, but on an event-by-event basis they may look very similar.

For M/Λ_v not large, v-gluino pairs will be produced in parton showers, just as light quarks and even charm quarks are pair-produced in QCD. Consequently the number of $\tilde{R}$ hadrons produced in an event may well be larger than two. In some cases (see below) this could lead to striking signatures. Note also that v-production of R-parity-even states, such as v-quarks, may generate $\tilde{R}$ hadrons in the final state through the parton showering.

Suppose now that $\tilde{R}$ and $\tilde{\chi}$, with mass M and m, lie close in mass, in particular with $M - m \lesssim \Lambda_v$. This may naturally occur if the bare gluino mass is small compared to Λ_v. Then the decay $\tilde{R} \to \tilde{\chi}$ plus v-hadrons may be forbidden. In this case decays such as $\tilde{R} \to Z\tilde{\chi}$ and $\tilde{R} \to h\tilde{\chi}$ may occur; though mediated by a loop-induced $g_v\tilde{g}_v\tilde{\phi}$ interaction, these will still typically be prompt, as the crude estimate

$$\begin{aligned}\Gamma_{\tilde{R}\to\tilde{\chi}Z} &\sim \alpha_2\theta_v^2\left(\frac{\alpha_v n_v n_H}{48\pi\hat{v}}\right)^2\Lambda_v^3 \\ &\gtrsim 2\times 10^{14}\ \mathrm{sec}^{-1}\left(\frac{\Lambda_v}{300\ \mathrm{GeV}}\right)^2 \\ &\quad\times\left(\frac{5\ \mathrm{TeV}}{\hat{v}}\right)^4\left(\frac{\theta_v}{v/\hat{v}}\right)^2 \qquad (8)\end{aligned}$$

demonstrates. A decay with a displaced vertex becomes more likely if $M - m \ll m_Z$, however, since in this case the rate receives an additional suppression by $\sim \alpha_2(M-m)^4/m_Z^4$. This phenomenon is not so different from neutralino decays in some GMSB models, which may produce a gravitino plus a Z and h, possibly at displaced vertices [12]; but photons are also generally produced as well in such models, while that is unlikely here.

If $\hat{v}$ is very large, direct v-quark or v-squark production rates via a Z' may be too small to observe. Even in this case, however, SM superpartner production offers another opportunity to discover the v-sector. During the cascade decays following sparticle production, mixing among neutralinos and/or Higgs bosons from the two sectors can allow v-sector particles to be produced, as shown in Fig. 6. While this will be a rare effect, the large cross-section for SM sparticle production means that this process can still be an important, or even the dominant, mechanism for v-hadron production.

G. Analogues in extra dimensional models, etc.

Essentially all of the remarks above have analogues in, for example, models with universal extra dimensions [20], or indeed dimensions of any sort, in which a $\mathbf{Z}_2$ symmetry (KK-parity) plays a role similar to R-parity in

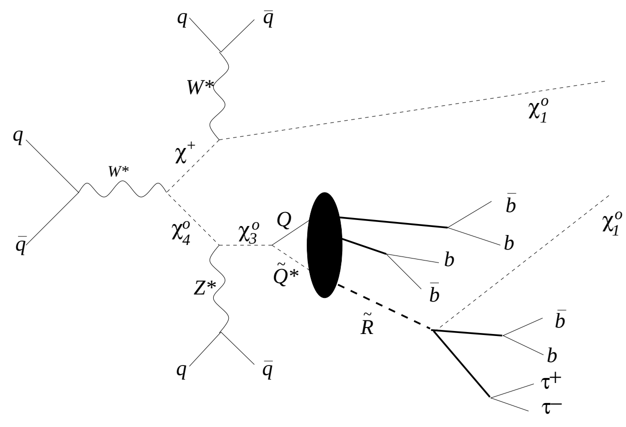

FIG. 6: Cascade decays following production of SM superpartners may occasionally lead, through neutralino mixing, to v-hadron production.

both the SM and the v-sector. The processes shown in Figs. 3, 5 and 6 can occur in these models as well, with chargino and neutralinos replaced with KK-excitations of charged and neutral vector bosons, the $\tilde{R}$ with a v-hadron containing the lightest $\mathbf{Z}_2$-odd KK-excitation of the v-gluon or a v-squark, *etc.* The phenomenology will be different in detail, but will at first experimental glance have similar features, in that the expected missing energy signals are diluted, soft jets are produced, *etc.*. This is in line with the remarks of [21]. Similar issues would apply to little Higgs models with a T-parity [22], assuming T-parity also acts on the v-sector.

A difference between these theories and supersymmetry is that the operators connecting the two sectors may be of higher dimension in the present case. For instance, squark decays to v-squarks may proceed via dimension five operators, while KK-quarks decaying to KK-v-quarks always do so through operators of dimension six. Thus the lifetime of the lightest KK-odd-quark may be longer, given the analogous spectrum, than that of a corresponding squark LSsP.

H. Final Remarks

Let us close with some remarks on the general search strategy that might be adopted by the collider experiments seeking to find or exclude these phenomena. First, from the present work and [6, 7], it should be clear that there is more than ample reason to make high-efficiency detection of highly displaced vertices an urgent priority in the last year of preparation for the LHC. Unlike most processes that will be sought at the LHC, this is one with no standard model background; all the backgrounds are instrumental. As such, it has rather different issues compared to those that trouble many searches at the LHC. In some scenarios, highly displaced vertices may be the key phenomenon allowing new signals to be identified and high-purity samples to be obtained. Comprehensive studies on a wide variety of highly-displaced vertex signals do not yet seem to have been done, but would be welcome. Efforts to improve track-finding algorithms might be an especially valuable use of resources.

Another potentially important issue is the efficiency for detecting large numbers of ordinary displaced vertices in events with many b jets and perhaps τ leptons. The classes of events considered here may be very busy, with multiple hard jets along with the soft jets from the v-hadron decays. In this context, the challenge of vertexing even with moderate efficiency seems daunting; but meeting this challenge successfully may be essential for finding supersymmetry or other new physics, and deserves additional consideration.

Given the vertexing capabilities of the LHCb detector, it would be well worth exploring its sensitivity to these phenomena. Despite the fact that the LHCb detector cannot reconstruct entire events and cannot therefore measure MET, as its coverage is limited to the forward direction, it may be especially capable of detecting the LSsP decays, or the ensuing v-hadron decays, some fraction of which will occur within its acceptance. Perhaps the LSsP and v-hadron decays will first be seen and analyzed at LHCb; the information thereby obtained will then be useful both for the CMS and ATLAS detectors in their analysis of supersymmetric production events, and for general efforts to understand the underlying supersymmetric model.

Finally, as should be evident, Tevatron limits on supersymmetric particle production, and other similar models, need to be reconsidered in this context. A comprehensive search for events with highly-displaced vertices might well reveal both a v-sector and the first signs of supersymmetry, or perhaps something else entirely unexpected. The author hopes that this work, and that of [6, 7], will be sufficiently motivating for the Tevatron experiments to undertake these difficult but important searches.

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